LLNL-PROC-414874

LAWRENCE LIVERMORE NATIONAL LABORATORY

Integrated Process Model Development and Systems Analyses for the LIFE Power Plant

W. R. Meier, T. Anklam, R. Abbott, A. Erlandson, W. Halsey, R. Miles, A. J. Simon

July 17, 2009

ICENES 2009
Ericeira, Portugal
June 29, 2009 through July 3, 2009

Integrated Process Model Development and Systems Analyses for the LIFE Power Plant

W.R. Meier[1], T. Anklam[1], R. Abbott[1], A. Erlandson[1], W. Halsey[1], R. Miles[1], A.J. Simon[1]

[1] Lawrence Livermore National Laboratory, Livermore, CA 94551

Abstract

We have developed an integrated process model (IPM) for a Laser Inertial Fusion-Fission Energy (LIFE) power plant. The model includes cost and performance algorithms for the major subsystems of the plant, including the laser, fusion target fabrication and injection, fusion-fission chamber (including the tritium and fission fuel blankets), heat transfer and power conversion systems, and other balance of plant systems. The model has been developed in Visual Basic with an Excel spreadsheet user interface in order to allow experts in various aspects of the design to easily integrate their individual modules and provide a convenient, widely accessible platform for conducting the system studies. Subsystem modules vary in level of complexity; some are based on top-down scaling from fission power plant costs (for example, electric plant equipment), while others are bottom-up models based on conceptual designs being developed by LLNL (for example, the fusion-fission chamber and laser systems). The IPM is being used to evaluate design trade-offs, do design optimization, and conduct sensitivity analyses to identify high-leverage areas for R&D. We describe key aspects of the IPM and report on the results of our systems analyses. Designs are compared and evaluated as a function of key design variables such as fusion target yield and pulse repetition rate.

1. Introduction

An integrated process model (IPM) for a Laser Inertial Fusion-Fission Energy (LIFE) power plant has been developed that includes cost and performance algorithms for the major subsystems of the plant, including the laser, fusion target fabrication, fusion-fission chamber (including the tritium and fission fuel blankets), heat transfer and power conversion systems, and other balance of plant systems. The model has been developed in Visual Basic with an Excel spreadsheet user interface in order to allow experts in various aspects of the design to easily integrate their individual modules and provide a convenient, widely accessible platform for conducting the system studies. In this paper we describe key aspects of the IPM and report on the results of our systems analyses for a particular design based on indirect-drive, hot-spot ignition (HSI) targets and a fission blanket using depleted uranium fuel. The cost of electricity (COE) is used as the figure of merit for design optimization and to reveal key cost and performance sensitivities. Additional details on the LIFE plant are given in Refs. 1-5.

2. Target Performance Scaling

The target gain and yield as a function of laser energy are shown in Fig. 1. Note that this is the laser energy that reaches the target after accounting for losses in transport through the low density Xe gas that fills the chamber to protect the first wall from x-ray and debris damage. This target performance assumes NIF-like illumination geometry. The IPM includes

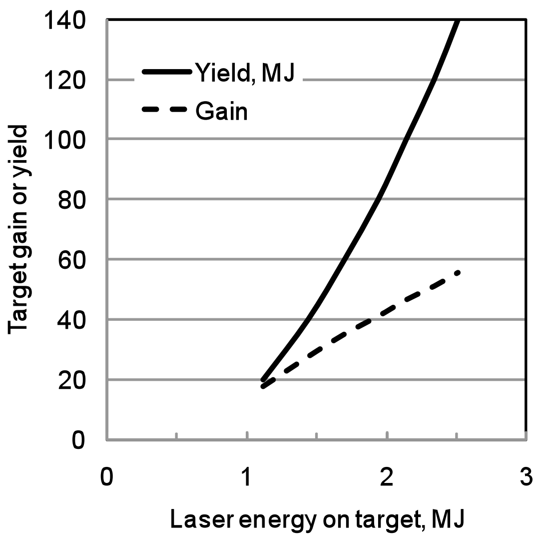

Fig. 1: Target gain (dashed) and yield (solid) as a function laser energy on target for hot spot ignition targets.

options for other target types (e.g., narrow cone angle illumination HSI targets and fast ignition targets with either spherical illumination or narrow cone angle illumination), but these are not considered here. As discussed later, LIFE plants will require target yields of 50-75 MJ, or 1.5-2 MJ on target.

3. Laser Scaling

Laser system capital costs are estimated from a combination of NIF historical data and expert judgment. NIF is a one-of-a-kind R&D facility whereas this paper is addressing an N'th-of-a-kind power plant. NIF unit costs have been adjusted to give credit for future manufacturing learning, account for non-recurring costs, such as supply chain development, and adjusted for beam line architecture differences between NIF and a LIFE power plant. The adjustments for learning and architecture improvements assumed for LIFE result in ~ 4× reduction in unit costs relative to comparable subsystems in NIF. Additional costs for systems needed for high pulse rate operation, such as the diodes and power conditioning, are added to arrive at the total LIFE laser cost. Figure 2 shows the laser cost as a function of laser energy at the final optic. The energy on target is somewhat lower, e.g., 10% for a 2.5 m radius chamber.

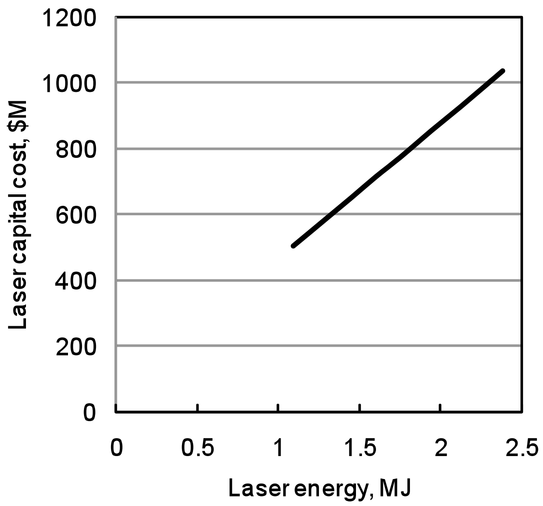

Fig. 2: Laser capital cost as a function of beam energy (0.35 μm) at the final optic.

Figure 3 show the laser cost as a function of pulse repetition rate (rep-rate). Varying the rep-rate by ±5 Hz about the 10 Hz point changes the capital cost by ±9%. This amounts to ~$17M/Hz.

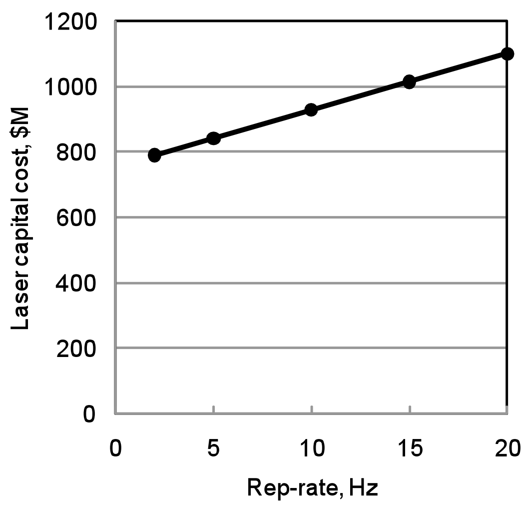

Fig. 3: Laser capital cost as a function of pulse repetition rate.

4. Target Costs

Target costs are based on a conceptual design of an automated target production facility (target factory) including estimates for buildings, process equipment, fixed and variable operating and maintenance costs. The sum of the annual capital-related charges, operation and maintenance (O&M) and feed materials gives a unit cost of \$0.22/target. For a plant operating at 10 Hz and a capacity factor of 85%, 2.7×10^8 targets are needed per year resulting in an annual target cost of ~\$59M. For a 1600 MW_e (net) power plant, this adds ~\$5/MWh to the COE.

5. Nuclear Island and Balance of Plant Cost Scaling

The costs for the nuclear island (NI) and balance of plant (BOP) are scaled from a reference, liquid metal cooled nuclear reactor by assuming analogous systems and structures.[6] The LIFE plant is similar to the liquid metal reactor in that neither technology requires the high pressure containment systems and structures typical of light water reactors, but both require intermediate coolant loops. Costs for the LIFE fusion target chamber and vacuum vessel, which are very different from a nuclear reactor pressure vessel, are calculated directly based on estimated raw material costs and an assumed fabrication cost multiplier. Additional allowances are included for LIFE unique systems such as tritium recovery, storage and special materials such as the molten salt coolants. Figure 4 shows the scaling of the NI plus BOP cost with gross electric power and illustrates the strong ecomony of scale, with costs going as $\sim(P/Po)^{0.55}$, where Po is some reference power. The scaling for the major subsystems of the plant (leading to this overall scaling) are on experience reported for fission reactors.[7]

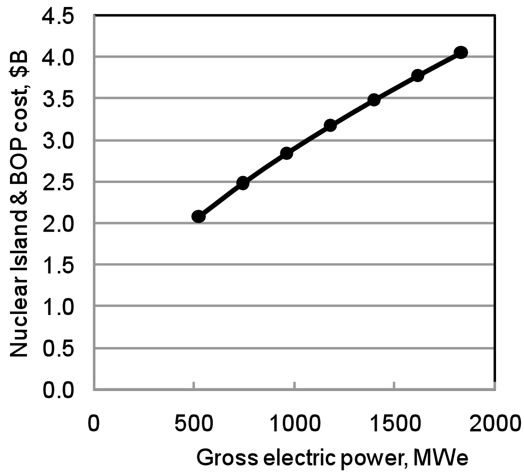

Fig. 4: Nuclear island and BOP cost as function of plant gross electric power.

6. Financial Assumptions and Methods

We have adopted the approach as reported in the MIT study for calculating the COE.[8,9] The power plant project is assumed to be financed with a combination of equity and debt financing yielding a nominal, tax adjusted cost of money of 7.8%. Annual costs are summed (accounting for the benefits of accelerated depreciation) and then deflated to 2007 dollars. This results in an effective fixed charge rate on capital investment of ~7.7%. The overnight construction cost, accounting for home and field office engineering, owners cost, etc. increases the direct capital cost by 59%. At this point we are assuming a uniform 10%, across the board contingency. Interest during construction is based on a 5 year construction period and increases the capital investment by ~10% (in 2007\$). Therefore the total capital cost (in 2007\$) is ~1.9 times the direct capital cost. In calculating the COE we assume a constant plant availability of 85%.

7. Results for Reference Design Point

Table 1 gives the key design parameters for an example reference design point. The laser energy on target is 1.89 MJ and produces a target yields of 75.6 MJ (target gain = 40). The overall energy multiplication in the tritium breeding and fission blankets (including fission product decay heat) is 5.35, so at 10 Hz, the thermal power is 4046 MW_t. The molten salt coolant with outlet temperature of 650 C drives a Brayton power cycle with a thermal conversion efficiency of 45%, generating 1831 MW_e gross electric power. The 12% efficiency laser requires 176 MW_e and we assume that 3% (55 MW_e) of the gross electric is required for in-plant auxiliary power needs. The plant net power is 1600 MW_e.

Table 1. Key Parameters for Reference Design.

Target type	Hot spot ignition
Fission fuel type	Depleted U
Laser energy at optic, MJ	2.12
Laser energy on target, MJ	1.89
Target gain	40
Target yield, MJ	75.6
Rep-rate, Hz	10
Fusion power, MW_t	756
Energy multiplication	5.35
Thermal power, MW_t	4046
Gross electric power, MW_e	1831
Laser efficiency, %	12
Laser power, MW_e	176
Auxiliary power, MW_e	55
Net electric power, MW_e	1600

Capital costs and the COE for the reference design are summarized in Table 2. The total overnight capital cost (TOC) is $5265 M with the nuclear island and BOP accounting for nearly 77%. The laser system has a capital of $927 M (~18% of the TOC). About 57% of the laser cost is due to diodes and power conditioning. Special materials, such as the beryllium multiplier and molten salt coolants, comprise 5.5% of the capital investment. The base case COE in fixed 2007$ is 51.3 $/MWh (or mills/$kW_e$h). Capital related charges account for 73% of the COE, O&M ~17%, and the fuel cycle which includes the fusion targets is 10.5% of the COE.

Table 2. Capital Costs and COE for the Reference Design Point.

Capital Costs	**M$**	**%**
Nuclear island	2210	42.0
BOP	1840	34.9
Laser diodes & PC	524	10.0
Main laser, transport & bldg	403	7.7
Special materials	288	5.5
Total Overnight Cost	**5265**	**100.0**
Cost of Electricity	**$/MWh**	**%**
Capital	37.4	72.9
O&M	8.5	16.6
Fuel cycle	5.4	10.5
Total COE	**51.3**	**100.0**

We find that these systems level COE estimates for LIFE are competitive with projections for future nuclear fission power plants. The MIT study (Ref. 9) cites 67 $/MWh for a 1000 MW_e LWR; scaled to 1600 MW_e , we estimate an LWR COE of 60 $/MWh. If advanced fission reactors achieve the same 45% conversion efficiency as we calculate for LIFE, we estimate COEs of 52 and 47 \$/MWh at net powers of 1000 and 1600 MW_e, respectively.

8. Design Space Studies

Next we examine the COE as a function of target yield, rep-rate and net electric power. Figure 5 shows the COE as a function of rep-rate for net powers of 1000, 1300 and 1600 MW_e. At each point, the laser energy and target yield are adjusted to keep the net power fixed. As indicated, the COE is relatively insensitive to rep-rate with 5-10 Hz near optimal for all three power levels. Larger plants have significantly lower COEs reflecting more economical use of the capital investment in the laser and the economy of scale benefits of the larger nuclear island and BOP (see Fig. 4).

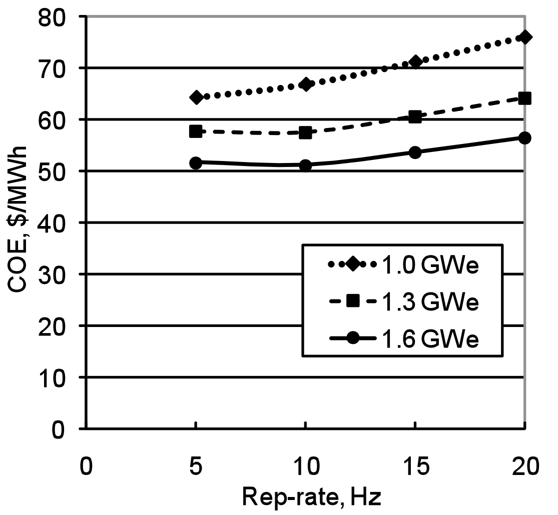

Fig. 5: COE as a function of rep-rate for fixed net power of 1000, 1300 and 1600 MW_e.

Figure 6 shows the COE as a function of target yield, again for three net electric powers. At very low yields, the target gain is low and the laser recirculating power is high, resulting in a high COE. COE decreases with increasing yield, with yields in the range of 50-75 MJ near optimal for this range of plant sizes. The markers on each line correspond to rep-rates of 20, 15, 10 and 5 Hz moving from left (low yield) to right.

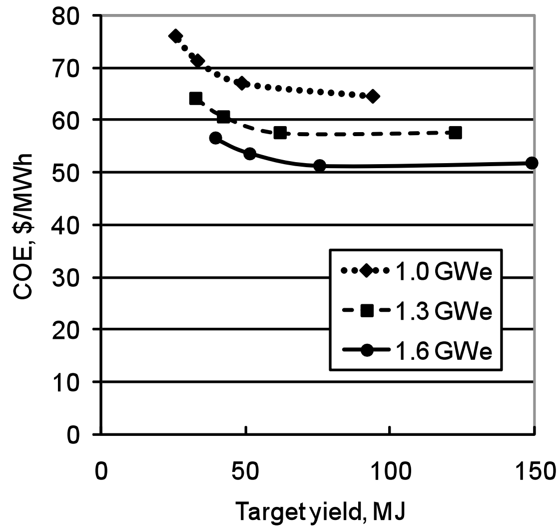

Fig. 6: COE as a function of target yield for fixed net power of 1000, 1300 and 1600 MW_e.

9. Sensitivity Studies

The sensitivity of the COE to uncertainties in capital costs can be derived from Table 2. For example, diodes and their power conditioning account for 10% of the capital cost, and the capital cost is 72.9% of the COE. Therefore, a factor of two change in diode and PC cost has a $0.1 \times 0.729 = 7.3\%$ impact on the COE. There is significant uncertainty in the cost estimate for the fusion target production. At \$0.22/target, fusion targets make up the majority of the fuel cycle cost, which is ~10% of the COE. A factor of two increase in the target manufacturing cost would increase the COE by ~10%.

The combined target gain of 40 and blanket gain of 5.4 coupled with the 12% laser efficiency leads to a modest recirculating power fraction for the laser; it is 176 MW_e out of 1831 MW_e or 9.6%. The sensitivity of the COE to laser efficiency is shown in Fig. 7. A factor of two change results in less than a 5% change in the COE. Note that as laser efficiency varies in this graph, the laser energy and target yield are adjusted to hold the net power fixed. Pulse rep-rate is also fixed at 10 Hz. Thus the lower laser efficiency is somewhat offset by the increased target gain.

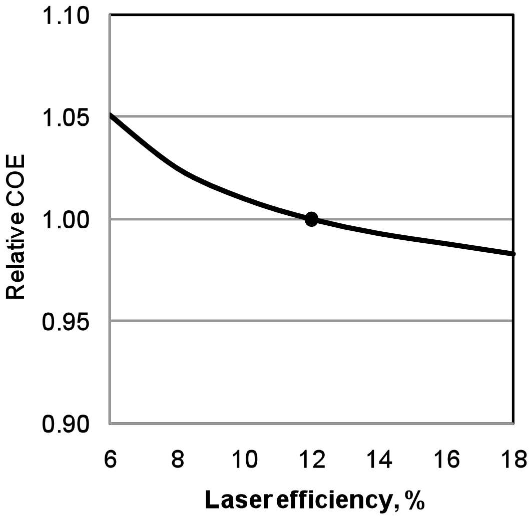

Fig. 7: COE as a function of laser efficiency. Net power fixed at 1600 MW_e.

The LIFE chamber is cooled with a LiF-BeF moltent salt (flibe). With an outlet temperature of 650 C, the power conversion efficiency is 45%. This high temperature capability is important to the economics of LIFE. As indicated in Fig. 8, if the thermal efficiency is reduced to 35%, typical of a water cooled reactor, the COE would increase by 16%. We are also exploring more advanced designs for LIFE using high temperature materials, e.g., SiC composites, that would allow higher conversion efficiencies. If 60% were achievable, the COE would decrease by 12%.

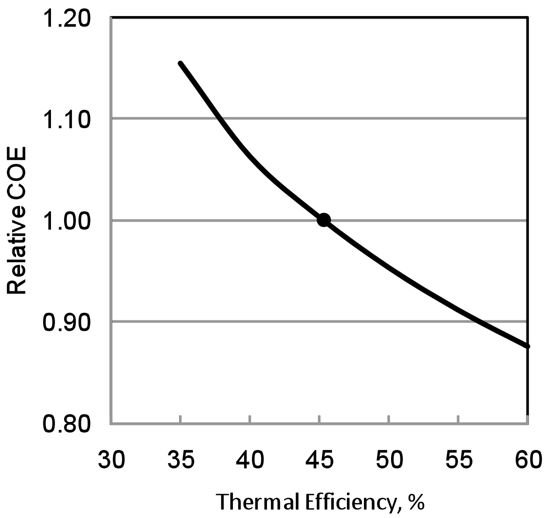

Fig. 8: COE as a function of thermal conversion efficiency. Net power fixed at 1600 MW_e.

While we have not completed the required nuclear and mechanical design analyses, we are considering versions of LIFE that would operate at higher fission blanket gain, i.e., higher k-effective. If the overall blanket multiplication can be increased from ~5 to ~10, the COE would decrease by ~7%.

10. Summary

The LIFE Integrated Process Model is being used to guide conceptual designs to attractive operating space and to identify high leverage R&D Scoping-level cost estimates indicate that LIFE can be competitive with fission power. Large plants (>1000 MW_e) are most cost effective. Fission blanket energy multiplication allows operation at modest target yields (~50-75 MJ), reducing required laser energy and cost. The COE is relatively insensitive to rep-rate for fixed net power and rep-rates of ~10 Hz or less are optimal. With estimated cost reductions relative to NIF, laser capital cost is only ~18% of the LIFE plant capital cost. Assuming LIFE nuclear island and

BOP costs are similar to fission plants, they account for 77% of total capital cost. We are now pursuing innovative low-cost, high-efficiency laser architectures and high-temperature, high efficiency chamber concepts to optimize the economics of LIFE.

Acknowledgements

The authors thank members of the LIFE R&D team for their many technical contributions to design and their assistance in developing the physics, engineering and cost scaling relationships incorporated in the Integrated Process Model. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

1. E. MOSES et al., "A Sustainable Nuclear Fuel Cycle Based on Laser Inertial Fusion-Fission Energy (LIFE)," *Fusion Science and Technology*, *accepted* (2008).

2. W. R. MEIER et al., "Systems Modeling for the Laser Fusion-Fission Energy (LIFE) Power Plant," *Fusion Science and Technology*, *accepted* (2008).

3. K.J. KRAMER et al., "Neutron Transport and Nuclear Burnup Analysis for the Laser Inertial Confinement Fusion-Fission Energy (LIFE) Engine," *Fusion Science and Technology, accepted* (2008).

4. R.P ABBOTT et al., "Thermal and Mechanical Design Aspects of LIFE Engine," *Fusion Science and Technology, accepted* (2008).

5. J. CAIRD et al., "Nd:Glass Laser Design for Laser ICF Fission Energy (LIFE)," *Fusion Science and Technology, accepted* (2008).

6. U.S. Advanced Liquid Metal Reactor Program – Actinide Recycle System: 1994 Capital and Busbar Cost Estimates," General Electric Report GEFR-00940/UC-87Ta (1995).

7. J.G. Delene et al., "Nuclear Energy Cost Data Base - a Reference Data Base for Nuclear and Coal-fired Power Plants Power Generation Cost Analysis," DOE/NE-0095 (Sept. 1988).

8. J.M. Deutch et al., "The Future of Nuclear Power – An Interdisciplinary MIT Study," ISBN 0-615-12420-8 (2003). http://web.mit.edu/nuclearpower/

9. J.M. Deutch et al., "Update of the 2003 MIT Future of Nuclear Power Study," MIT report (2009). http://web.mit.edu/nuclearpower/